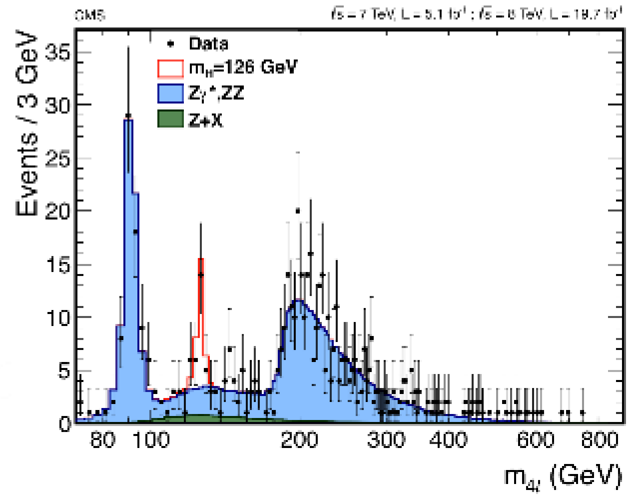
A few Proposals for Precision Particle Physics

Speaker: *prof. Franco Simonetto*

Way to a discovery

- Blatant:
  - see a new particle



- Subtle:
  - Look for anomalies
    - ***Inconsistencies*** between theory prediction and measurement

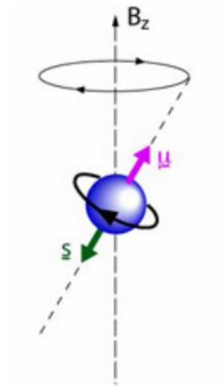
$$gyromagnetic\ anomaly\ g-2$$

    - Tiny effects ***not expected*** by the theory

$$CP\ -violation\ in\ \bar{b}\ b\ mixing$$

The e gyromagnetic factor

- The electron magnetic moment is responsible for its spin precession in a magnetic field



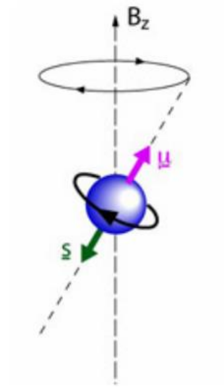
- Gyromagnetic ratio:
  - $\gamma_e = \frac{\mu}{S} = -\frac{e}{2m_e} g_e$
- Dirac theory (1928):
  - $g_e = 2$ (exact !),
  - $a_e = \frac{g_e - 2}{2} = 0$
- Kush & Foley (1947):
  - $a_e = (1.19 \pm 0.04) \times 10^{-3} \simeq \frac{\alpha}{2\pi}$

"anomalous magnetic factor"

Birth of QED

The e gyromagnetic factor

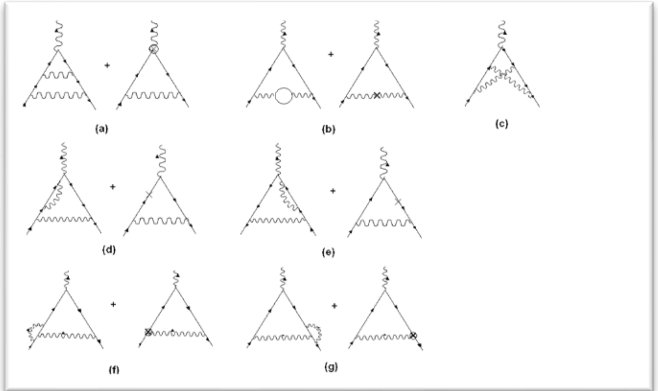
- The electron magnetic moment is responsible for its spin precession in a magnetic field



- Gyromagnetic ratio:
  - $\gamma_e = \frac{\mu}{S} = -\frac{e}{2m_e}\, g_e$
- Dirac theory (1928):
  - $g_e = 2$ (exact !),
  - $a_e = \frac{g_e - 2}{2} = 0$
- Kush & Foley (1947):
  - $a_e = (1.19 \pm 0.04) \times 10^{-3} \simeq \frac{\alpha}{2\pi}$
  - Nowadays:

3×10^{-11} relative precision !

  - $a_e = \left(1.15965218076(28)\right) \times 10^{-3}$
  - $\alpha = \frac{e^2}{4\pi\epsilon_0 \hbar c} = \left(137.035999150(33)\right)^{-1}$



The μ *anomaly*

- Very precise measurement through muon spin precession in a storage ring (BNL + Fermilab):

4×10^{-8}relative precision !

$$a_\mu = 1.16\,592\,061(41) \times 10^{-3}\ \text{(experiment)}$$

- Very precise calculation based on perturbative QED:

$$a_\mu = 1.16\,591\,810\ (43) \times 10^{-3}\ \text{(theory)}$$

- Comparable and astounding precision !

The μ *anomaly*

- Very precise measurement through muon spin precession in a storage ring (BNL + Fermilab):

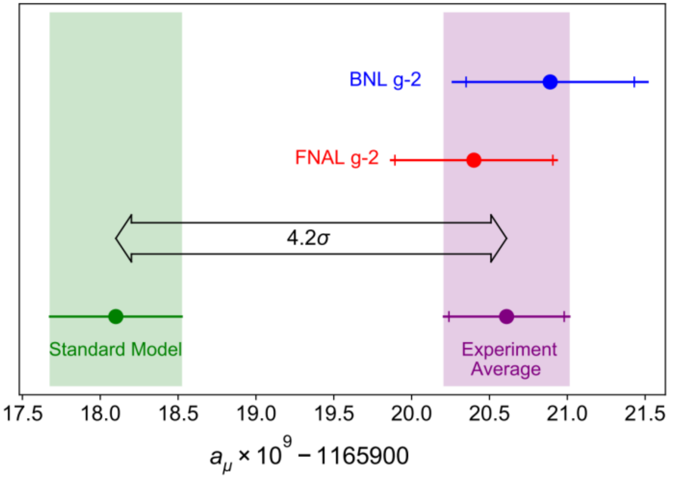
4×10^{-8} relative precision !

$$a_\mu = 1.16\,592\,061(41) \times 10^{-3} \text{ (experiment)}$$

- Very precise calculation based on perturbative QED:

$$a_\mu = 1.16\,591\,810\,(43) \times 10^{-3} \text{ (theory)}$$

- … ***but inconsistent results***



$$\boldsymbol{a_\mu(ex.) - a_\mu(th) = (259 \pm 51) \times 10^{-11}\ (4.2\,\sigma\,!)}$$

The muon *anomaly*

- Very precise measurement through muon spin precession in a storage ring (BNL + Fermilab):

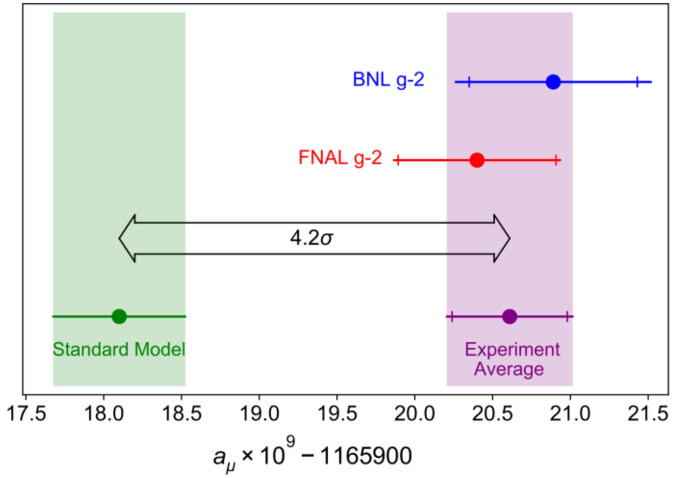
4×10^{-8} relative precision !

$$a_\mu = 1.16\,592\,061(41) \times 10^{-3}\ \text{(experiment)}$$

- Very precise calculation based on perturbative QED:

$$a_\mu = 1.16\,591\,810\,(43) \times 10^{-3}\ \text{(theory)}$$

- … ***but inconsistent results***



- An experimental mistake?
- Wrong calculations ?
- New physics lurking ?

Theory

- a_μ is computed with perturbation theory in the framework of QED
- Contributions from:
  - Photon exchange
  - Z exchange
  - ***Hadron exchange***

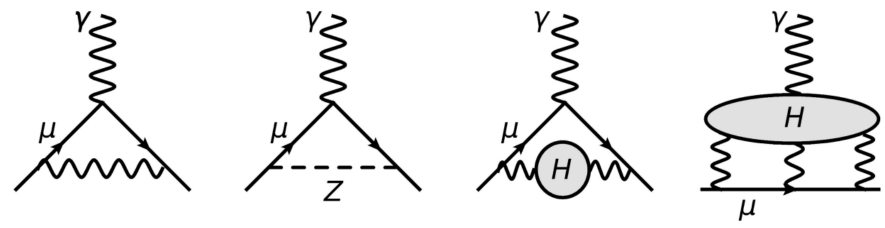


FIG. 1. Feynman diagrams of representative SM contributions to the muon anomaly. From left to right: first-order QED and weak processes, leading-order hadronic (H) vacuum polarization and hadronic light-by-light contributions.

Theory

- a_μ is computed with perturbation theory in the framework of QED
- Contributions from:
  - Photon exchange
  - Z exchange
  - ***Hadron exchange***

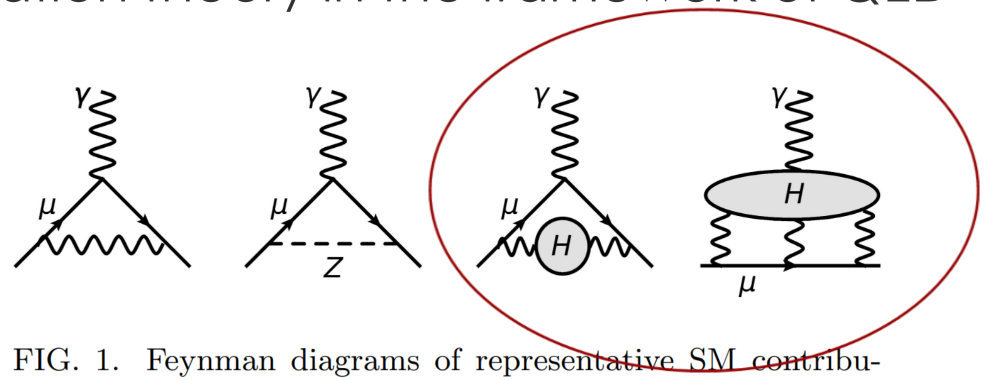


FIG. 1. Feynman diagrams of representative SM contributions to the muon anomaly. From left to right: first-order QED and weak processes, leading-order hadronic (H) vacuum polarization and hadronic light-by-light contributions.

- Are HADRONIC contributions reliable ?
- ***μOnE*** :
  - an experiment to help theory

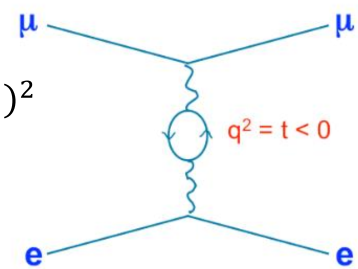
The MuOnE proposal

C.M. Carloni Calame, M. Passera, L. Trentadue, G. Venanzoni Phys.Lett. B746 (2015) 325

- ***Precise measurement*** of the differential x-section:

$$\frac{d\sigma(\mu^- e^- \to \mu^- e^-)}{dt}$$

$$t = (p_\mu - p'_\mu)^2 = (p'_e - p_e)^2$$

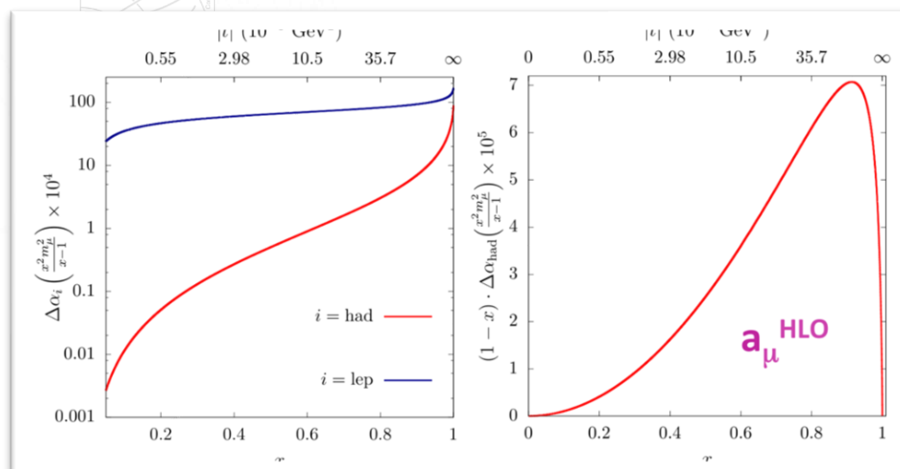


  - Electro-Weak contributions well known
  - Hadronic contributions computed by subtraction

$$a_\mu^{HLO} = \frac{\alpha}{\pi}\int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)]$$

- $\Delta\alpha$: running coupling constant, to be measured by MuOnE
- $\Delta\alpha_{had}$: hadronic contribution, computed by subtraction of EW terms

$$t(x) = -\frac{x^2 m_\mu^2}{1-x} \qquad 0 \le -t < \infty \qquad 0 \le x < 1$$

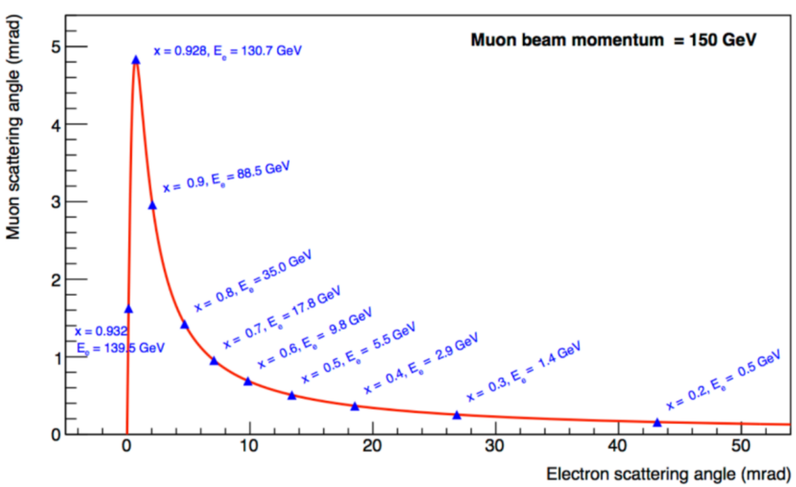


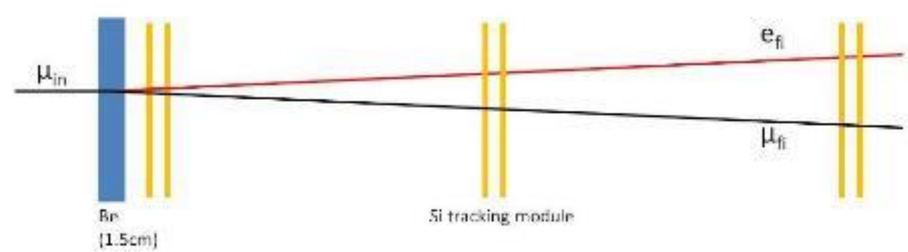
MuOnE: the mission

- Measure the running of α in the range $0 < |t| < 0.130\ GeV^2$
- To be competitive, need $\sigma(a_\mu^{had}) \simeq\ 0.5 - 1\ \%$
- $\frac{a_\mu^{had}}{a_\mu} \simeq 10^{-3}\ \rightarrow \qquad \frac{\sigma(\Delta\alpha)}{\Delta\alpha} \simeq 10^{-5}!$
- Extreme precision is required:
  - Large number of collisions (o(10^{10}))
  - Very refined control of systematic uncertainties

MuOnE: $e\mu \to e\mu$ kinematics

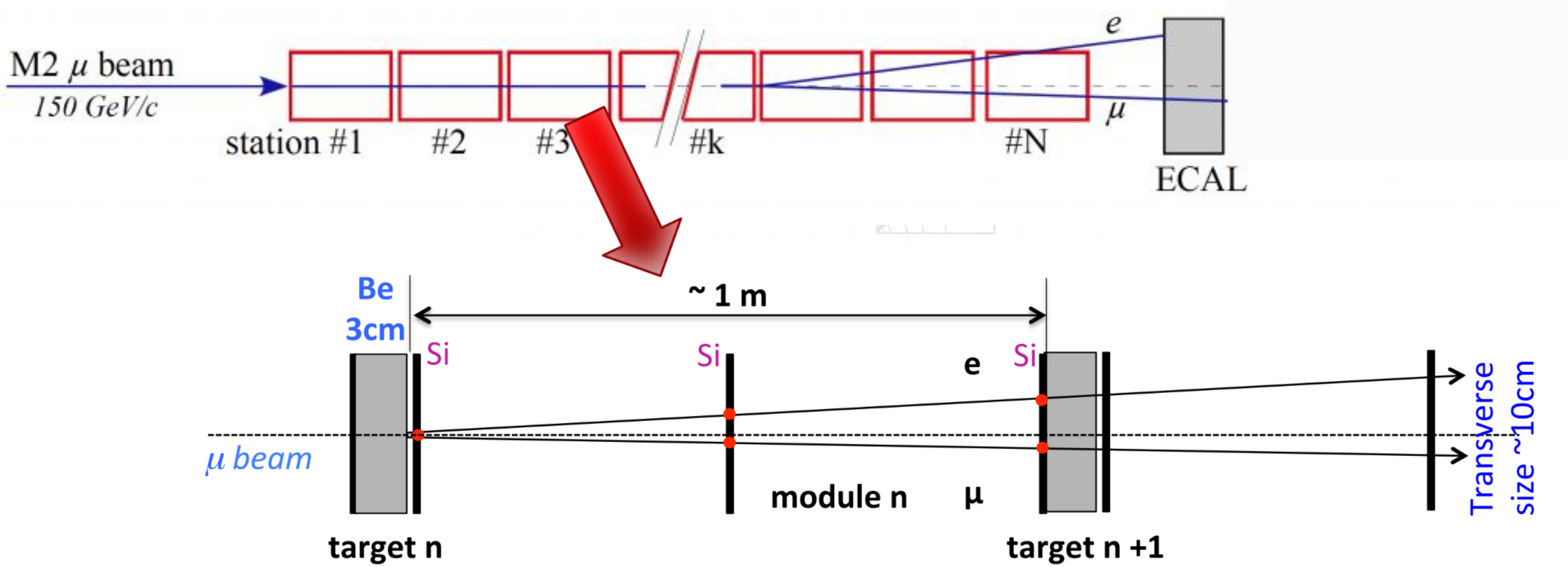
- Two body elastic scattering
- The kinematics is fully determined by measuring just two quantities
- MuOnE (proposal):
  - Send a high energy μ beam on a target of rest electrons
  - Measure the angles of the deflected muon (θ_μ) and electron (θ_e)





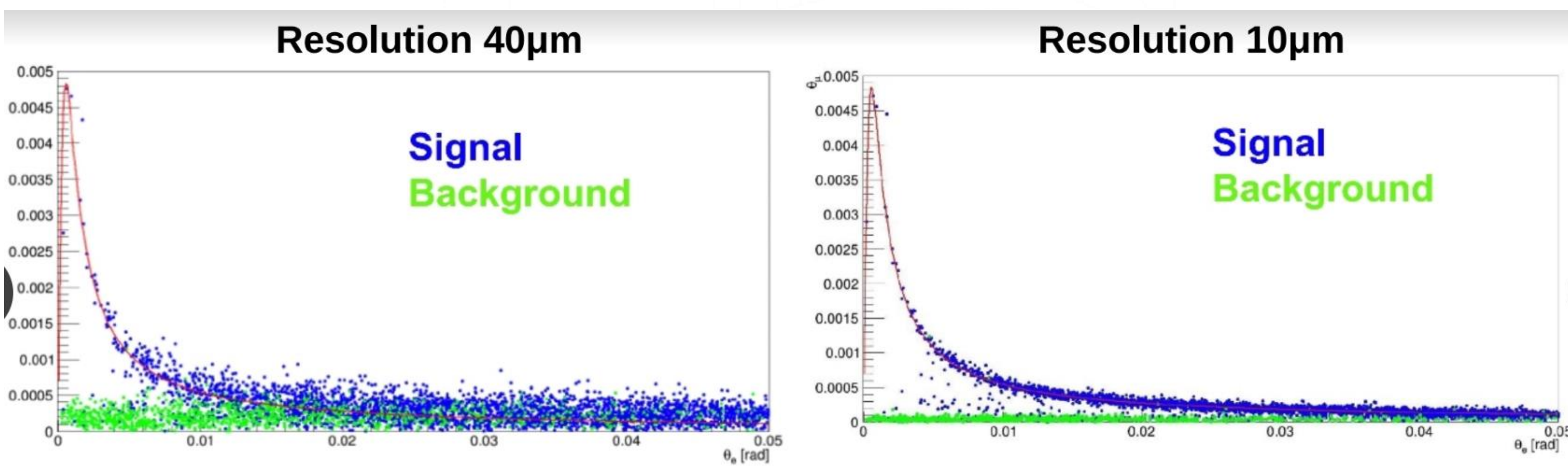
MuOnE: the proposal

- High intensity ($10^7 \mu\, s^{-1}$) 150-GeV muon beam from CERN SPS
- 40 tracking stations, each composed by a Be target and Si detectors
- An electromagnetic calorimeter at the end



The tracker

- Precise determination of e and μ scattering angles
  - $\theta_\mu \simeq 1-5\, mrad,$
  - $\theta_e \simeq 1-30\, mrad$
- Resolution:
  - Multiple scattering $\sigma(\theta_e) \simeq 10^{-2}\, mrad$
  - Requires alignment with ~10 μm precision

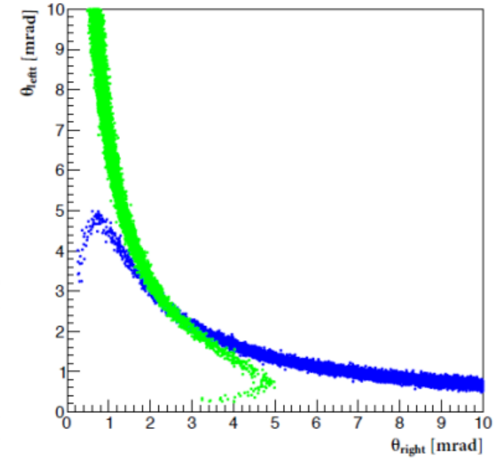


The Calorimeter

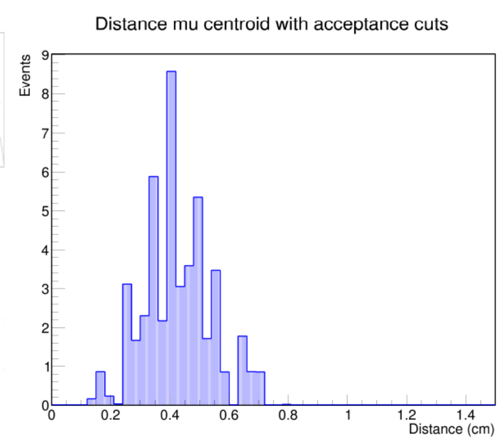
- Focus of Padova group:
  - Dr. E.Conti (group leader)
  - Prof. P.Ronchese
  - Dr. Eng. Fabio Montecassiano
  - Dr. Enrico Lusiani
- Roles:
  - Solve ambiguities through particle identification
  - Selection of truly two-body events
  - Independent measurement of t

Particle ID to solve Ambiguities

- When $\theta_e \simeq \theta_\mu$ $(and\ E_e \simeq E_\mu)$ the two particles cannot be distinguished exploiting kinematics



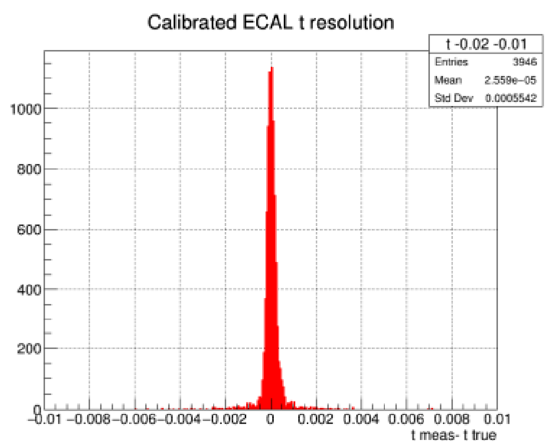
- In the Ecal the muon releases a mip signal (E<1 GeV), while the electron releases a large shower (E = 70-80 GeV)

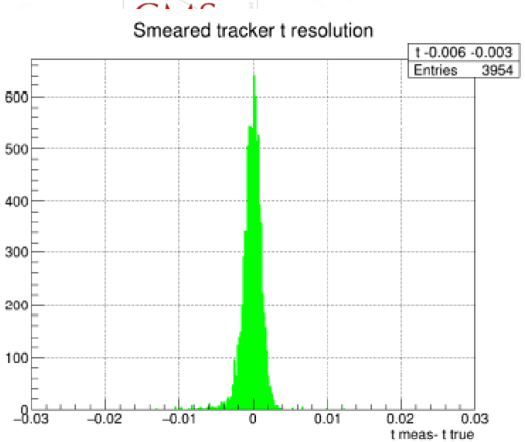


- Association of the large shower to the e track solves the ambiguity (Sara Cesare thesis, based on fast simulation)

Calorimetric measurement of t

- The virtual photon mass can be measured from Calo alone:
  - $t = (p'_e - p_e)^2 = -2\, m_e (E_e - m_e) = -2 m_e (E_{CAL} - m_e)$
- Preliminary studies show that this measurement is more precise than tracking (Sara Cesare thesis, fast simulation)





Calorimeter prototype

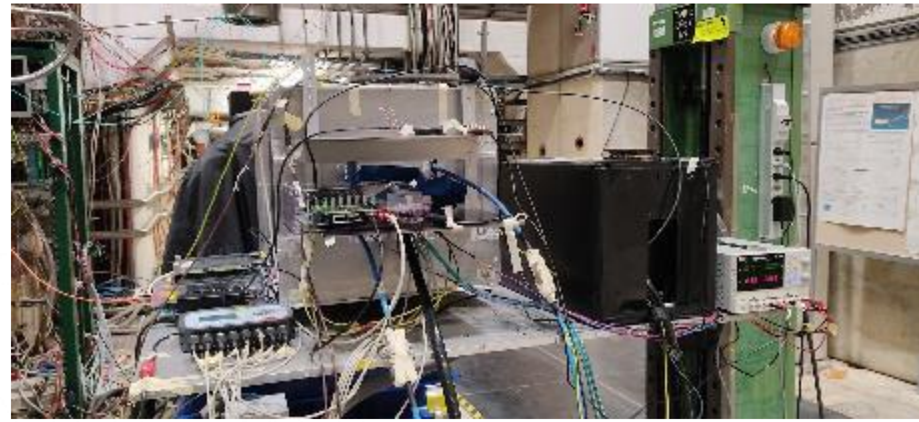
- Prototype array, 5x5 fully equipped PbWO4 crystals
  - Spare counters from CMS setup
  - Electronic board from Imperial College
- Intense testing campaign with test pulses and cosmic rays in LNL
- Brought to CERN in 2022 for tests on High Energy e and μ beams

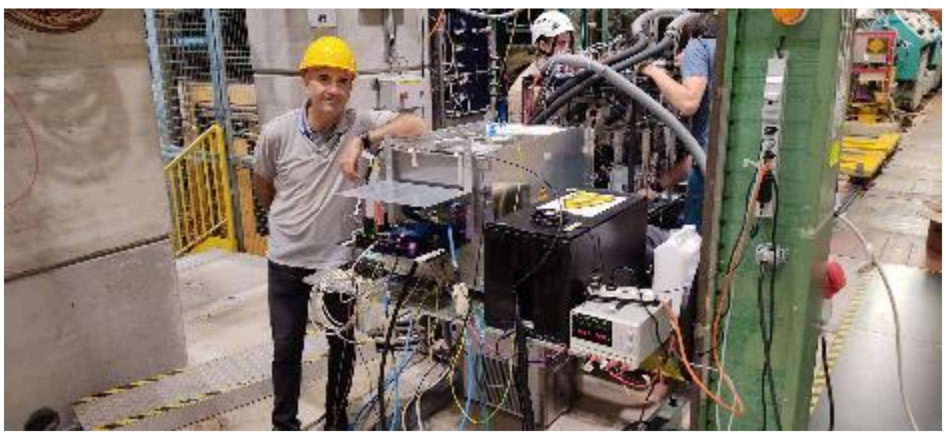
Test beam experiments, past

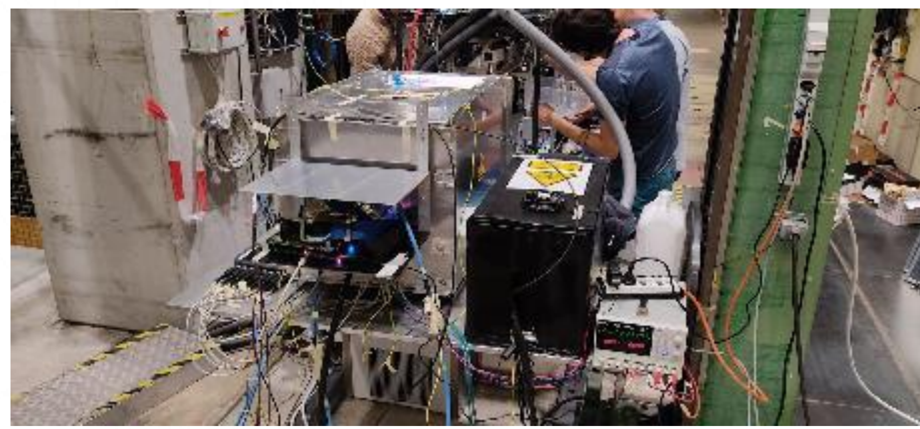
- Five runs on beams already performed at CERN:
  - July 2022: standalone test on low energy electron beam
  - Oct 2022: test with a tracking station with high-energy electron and muon beams
  - June 2023: 3-week calibration test with medium to high energy electron beams
  - Sept 2023: Physics run with two tracking stations, aimed at a few % measurement of the cross section and running of α

LOTS OF DATA TO ANALYZE

October 23 test beam







CERN Nord Area (Prevessin) 150 GeV μ beam, 40 GeV e beam

Test beam experiments, future

- New data taking on July 2024
  - Physics run with **three** tracking stations, aimed at a few % measurement of the cross section and running of α

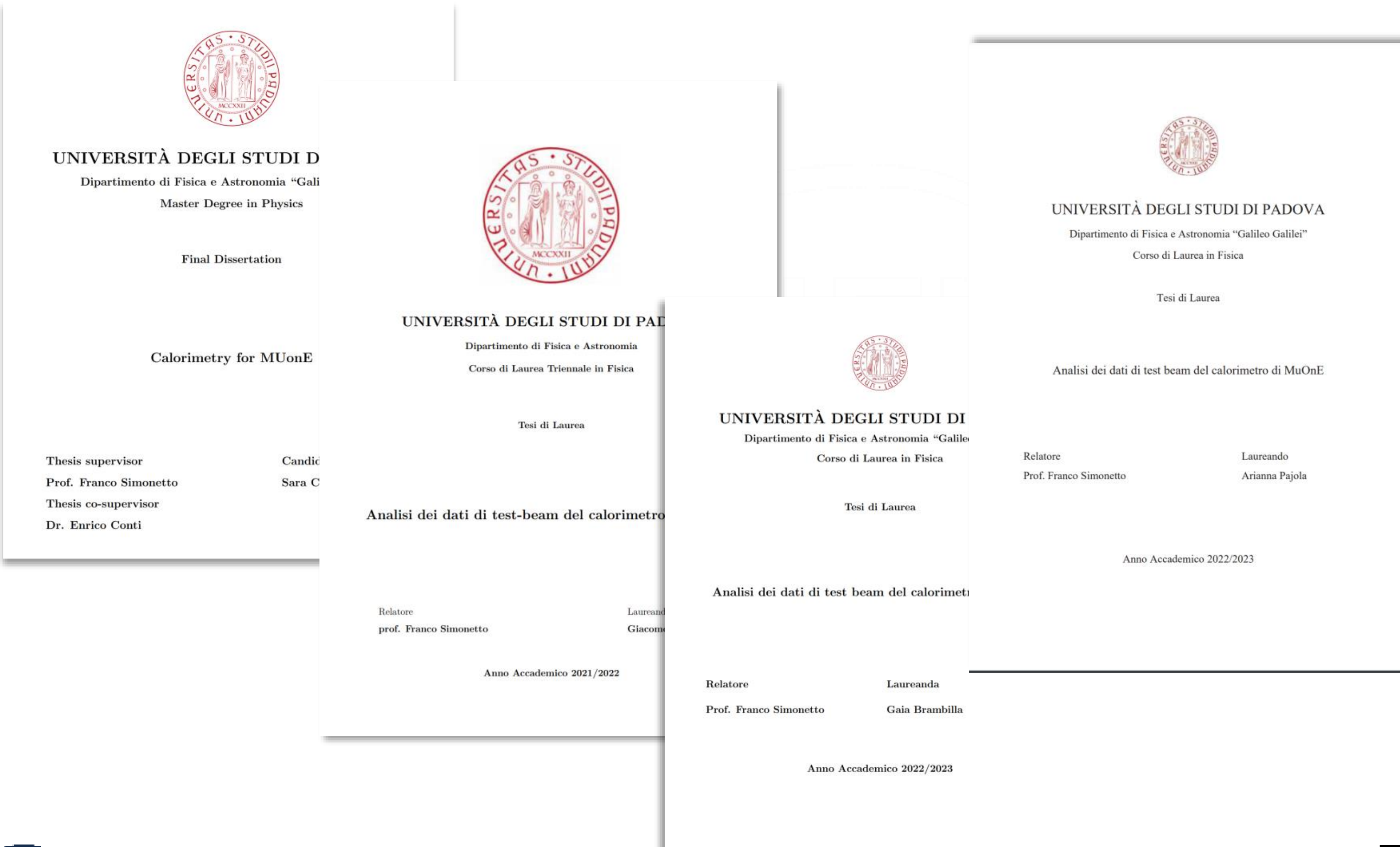
LOTS OF DATA TO HARVEST AND ANALYZE

Calorimeter studies, aka items for Bachelor & Master thesis

- Conclude the analysis of the data collected so far
  - Tracker-calo match algorithms
  - Cross section measurement
- Prepare for July CERN test beam
  - … and take part to it *(Master only)*
- Analyze new test beam data
- Lots of simulation study to move from prototype to full set up

Previous works

- Many thesis completed so far:



UNIVERSITÀ DEGLI STUDI D
Dipartimento di Fisica e Astronomia "Gali
Master Degree in Physics

Final Dissertation

Calorimetry for MUonE

Thesis supervisor
Prof. Franco Simonetto
Thesis co-supervisor
Dr. Enrico Conti

Candid
Sara C

UNIVERSITÀ DEGLI STUDI DI PAD
Dipartimento di Fisica e Astronomia
Corso di Laurea Triennale in Fisica

Tesi di Laurea

Analisi dei dati di test-beam del calorimetro

Relatore
prof. Franco Simonetto

Laureand
Giacom

Anno Accademico 2021/2022

UNIVERSITÀ DEGLI STUDI DI
Dipartimento di Fisica e Astronomia "Galile
Corso di Laurea in Fisica

Tesi di Laurea

Analisi dei dati di test beam del calorimet

Relatore
Prof. Franco Simonetto

Laureanda
Gaia Brambilla

Anno Accademico 2022/2023

UNIVERSITÀ DEGLI STUDI DI PADOVA
Dipartimento di Fisica e Astronomia "Galileo Galilei"
Corso di Laurea in Fisica

Tesi di Laurea

Analisi dei dati di test beam del calorimetro di MuOnE

Relatore
Prof. Franco Simonetto

Laureando
Arianna Pajola

Anno Accademico 2022/2023

Previous works

- Many thesis completed so far:

UNIVERSITÀ DEGLI STUDI D
Dipartimento di Fisica e Astronomia "Gali
Master Degree in Physics
Final Dissertation
Calorimetry for MUonE
Thesis supervisor — Prof. Franco Simonetto
Thesis co-supervisor — Dr. Enrico Conti
Candid — Sara C

UNIVERSITÀ DEGLI STUDI DI PAD
Dipartimento di Fisica e Astronomia
Corso di Laurea Triennale in Fisica
Tesi di Laurea
Analisi dei dati di test-beam del calorimetro
Relatore — prof. Franco Simonetto
Laureand — Giacom
Anno Accademico 2021/2022

UNIVERSITÀ DEGLI STUDI DI
Dipartimento di Fisica e Astronomia "Galile
Corso di Laurea in Fisica
Tesi di Laurea
Analisi dei dati di test beam del calorimet
Relatore — Prof. Franco Simonetto
Laureanda — Gaia Brambilla
Anno Accademico 2022/2023

UNIVERSITÀ DEGLI STUDI DI PADOVA
Dipartimento di Fisica e Astronomia "Galileo Galilei"
Corso di Laurea in Fisica
Tesi di Laurea
Analisi dei dati di test beam del calorimetro di MuOnE
Relatore — Prof. Franco Simonetto
Laureando — Arianna Pajola
Anno Accademico 2022/2023

… but there's plenty of things still to be done

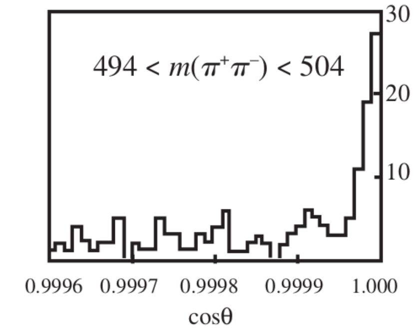
Why join MuOnE ?

- Small size HEP experiment, with a well-defined aim, in the biggest HEP lab of the world:
  - Know all your colleagues !
  - Connect with other Italian and foreign institutions
  - Good/excellent understanding of all the theoretical and experimental details (including those you are not directly involved in)
- Take part to a world-class measurement, bound to be reported in the textbooks of HEP
- A human friendly time span
  - ~ 5 years from design (now!) to completion
  - See results before retirement !
- You are offered the possibility to acquire many different skills:
  - Detector simulation programs
  - Data analysis
  - Hardware setup
- Work side by side with a friendly bunch of researchers

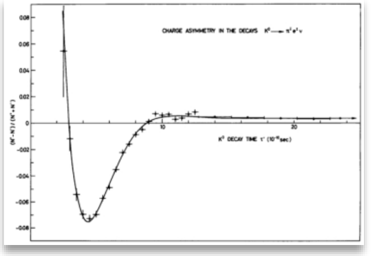
… and a very friendly team

CPV in $\bar{b}b$ mixing

- 1964: Christenson & co observe $K_L \rightarrow \pi\pi$ decay
  - CP violation is discovered
  - Tiny effect, o(permille)



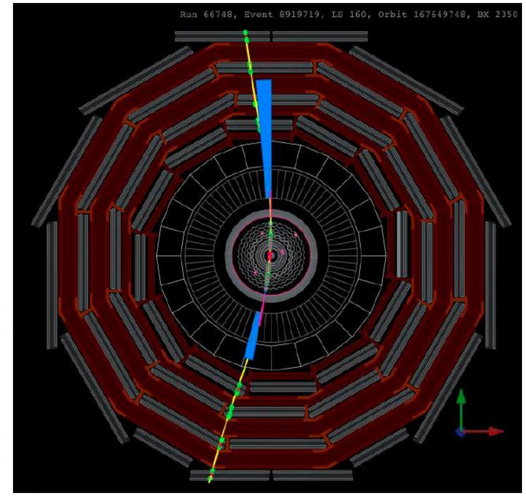
- 1972: $Prob(K_L \rightarrow e^+\pi^-\nu_e) > Prob(K_L \rightarrow e^-\pi^+\bar{\nu}_e)$
  - CP violation in discovered
  - Tiny effect, o(permille)



- 2001: BABAR and Belle observe B mesons to violate CP
  - First observation outside the Kaon systems
  - *Noboy has yet observed CP violation in $B\bar{B}$ mixing !*
  - *Standard model expectation o(10^{-4}) or less*

CPV at CMS ?

- CMS detector at the LHC:
  - Record solenoidal magnetic field
  - Superb track reconstruction
  - Excellent muon reconstruction



- A lot of opportunities for CPV measurements with data on disk:
  - About 10^{10} $b \to \mu\,\bar{\nu} X$ decays
  - O(10^{6}) $pp \to \bar{b}b\,X \to B^{+}(\mu^{+}\mu^{-}\,K^{+})\,\mu\,Y$
  - O(10^{7}) $t \to \ell\bar{\nu}b$ decays

CPV-mix in a nutshell

- Target:
  - Measure $A_{cp} = \frac{\{N(BB)-N(\bar{B}\bar{B})\}}{N(BB)+N(\bar{B}\bar{B})}$ with permille or better precision
- Way
  - Tag one B by a final state muon
  - Tag the other by:
    - Another muon
    - A fully reconstructed B+
    - Semileptonic top decay

Three independent analysis streams

- Challenges. Control at permille level:
  - Tag asymmetries
  - Background
  - Biases

The crew:
- dr E. Lusiani
- prof. M.Margoni
- prof. P.Ronchese

Required skills

- Basic competence in statistics and data analysis, as acquired in the LAB courses
- Basic competence with C++ programming, elementary knowledge of the ROOT-CERN analysis package
- Attitude to group work
- … much more will be learned during the thesis work

Contact

Speaker:

prof. Franco Simonetto

Group Muone:

dr Enrico Conti
dr Enrico Lusiani
prof. Paolo Ronchese
prof. Roberto Rossin
dr. Eng. Fabio Montecassiano

Group CMS:

dr Enrico Lusiani
prof. Paolo Ronchese
prof. Martino Margoni

email:

name.surname@pd.infn.it